The emergence of agropastoralism: Accelerated ecocultural change on the Andean altiplano, ~3540–3120 cal BP

Erik J. Marsh

CONICET, Laboratorio de Paleo-Ecología Humana, Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Mendoza, Argentina

In the fourth millennium BP, there were major environmental and cultural changes on the Andean altiplano of South America, but the chronology remains vague. A recent synthesis describes a slow, gradual transition from hunting and gathering to agropastoralism. This proposal is tested by refining the date of the onset of more humid and stable conditions, around 3550 cal BP, based on a Bayesian model of 26 dates from Lake Wiñaymarka and an updated calculation of the lacustrine offset. This is compared to Bayesian models of 191 dates from 20 archaeological sites, which incorporate a number of recently processed radiocarbon dates. A synthesis is presented of 15 full coverage surveys, a summed probability distribution, and a Bayesian model of the transition to ceramics, which together support a scenario of a very rapid demographic increase. Fourteen models from archaeological sites are cross-referenced in a composite model, which identifies a brief, altiplano-wide emergence of agropastoralism with starting and ending boundaries of 3540 and 3120 cal BP, respectively. This starting boundary correlates strongly with the onset of improving environmental conditions, indicating synchronous cultural and environmental change. The suite of accelerating cultural changes included a marked reduction in mobility, a demographic surge, increased subsistence diversity, the adoption of ceramics, farming and the integration of camelid herding into a remarkably resilient economic strategy still in use today. This is a highly relevant but yet to be used comparative case study for the variable tempos of 'big histories', and ecocultural interactions that generate rapid, emergent episodes of wide-spread and enduring cultural change.

Keywords: Bayesian models, Radiocarbon dates, Synchronous cultural and environmental change, Episodes of accelerating history, Emergence of agropastoral practices, Andes, Altiplano, Peru, Bolivia, South America

Introduction

The Lake Titicaca Basin and central altiplano of highland South America have been occupied by humans for roughly the last ten thousand years. During this time, there have been relatively few moments of profound cultural change: the initial occupation by hunter–gatherers, the emergence of agropastoralism, the rise and fall of the Tiwanaku state, and European contact. Each involved enduring changes to peoples' lifestyles throughout the region, and seem to be linked to macro-scale environmental changes (Gosling and Williams 2013). However, fine-grained chronologies are necessary to better address how people and communities perceived and interacted with the environment. In the case of the emergence of agropastoralism, the relationship between cultural and environmental shifts remains unclear because chronologies remain imprecise. Rates of change are even more vague. This article's goal is to refine the chronology and rate of the emergence of agropastoralism and test its temporal correlation with climate change.

The consensus view follows Browman (1981, 409), that in the centuries following 4000 BP, people began using new technologies, namely ceramics, and relied on a range of domesticated plants (Hastorf 2008). Village life was established, involving a major demographic shift that included new settlements and population growth (Bandy 2001, 280–281). The climate became more amenable as precipitation increased and became more regular (Abbott *et al.* 1997a). Agropastoral practices were adopted throughout a vast region, from the northern Lake Titicaca Basin to the central altiplano (Fig. 1). These practices, still in use today, have proved to be effective and resilient, even in the face of powerful external impacts, such as

Correspondence to: Erik J. Marsh, CONICET, Laboratorio de Paleo-Ecología Humana, Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Padre Jorge Contreras 1300, Parque General San Martín (M5502JMA), Mendoza, Argentina.
Email: emarsh@mendoza-conicet.gob.ar

DOI 10.1179/1749631414Y.0000000036

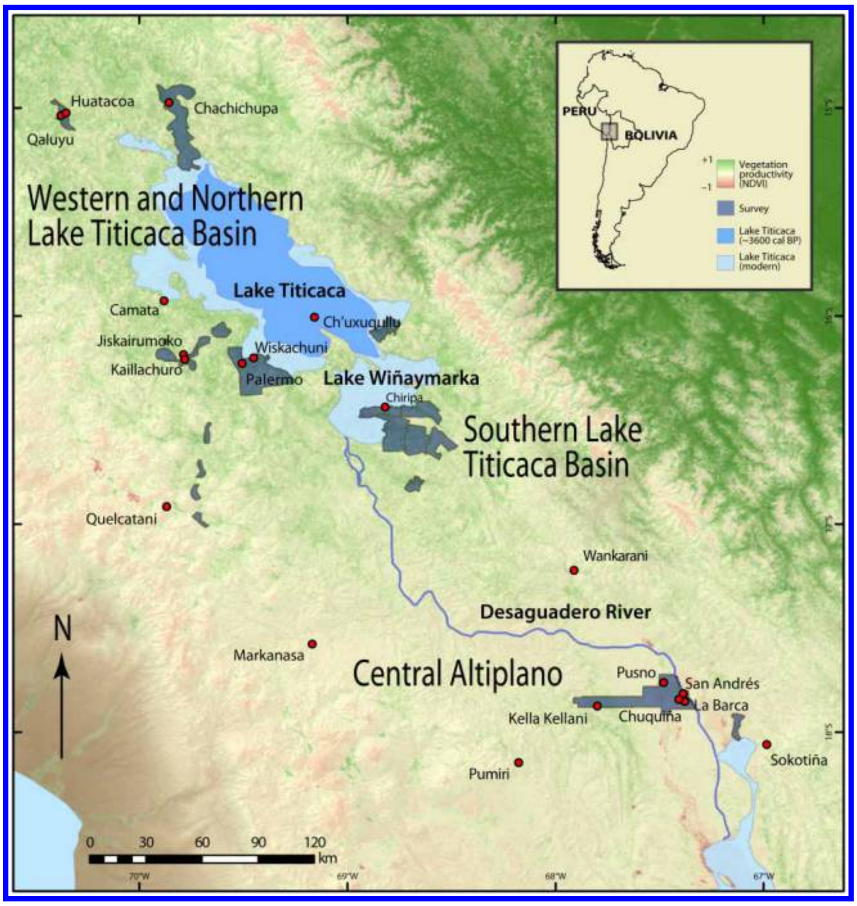

Figure 1 The Lake Titicaca Basin and central altiplano, showing the 20 sites with relevant radiocarbon dates and 15 full coverage surveys. Light blue lake areas indicate current shorelines; the darker blue area is the approximate extent of Lake Titicaca until ~3600 cal BP, 90 m below its current 3810 masl (based on D'Agostino *et al.* 2002, Figure 14). Two overlapping layers show (1) topography, as hillshading of an ASTER Digital Elevation Model and (2) vegetation productivity, estimated as the Normalised Difference Vegetation Index (NDVI), based on 32-day composite MODIS imagery, February–March 2001. Satellite data courtesy of NASA and the US Geological Society, accessed through the Global Land Cover Facility.

major droughts, ENSO events, the arrival of the Inca and Spanish Empires and modern market capitalism.

Although these practices have clearly endured, the nature and tempo of their emergence remain unclear. Disparate and geographically scattered evidence for the origins of these practices has not coalesced into a clear interpretation of this transition. Stanish (2003, 99–100) has proposed that this 'was a long process, not an event, … [which] evolved over millennia'. This reasonable generalisation accommodates the sparse and sometimes incongruent data. However, it relies heavily on an evolutionary model of social development, including the dubious assumption that change towards complexity occurs slowly (Rowley-Conwy 2001, 54–56). Regional 'big histories' may be non-linear and punctuated by episodes of accelerated change. These episodes can be treated as emergent phenomena within complex natural systems (e.g. McGlade 1995; van der Leeuw and McGlade 1997; Lehner 2000; Bentley and Maschner 2003; Sawyer 2004; Baden 2005; see overview in Marsh 2012a, 46–50).

An accelerated tempo of change makes dynamic periods challenging to document archaeologically (Pauketat 2001). Doing this requires increasingly precise chronological methods and radiocarbon dates. Many recently processed dates have not been integrated into regional interpretations, and many are only available in unpublished theses (Table 1, Supplement 1). Here I explore this growing set of dates with Bayesian models, an attractive alternative to the traditional approach of 'eyeballing' uncalibrated dates, especially relevant for large sets of dates from large regions.

I use Bayesian models to test the alternative hypothesis that the development of agropastoral practices was a rapid, emergent episode correlated with improving environmental conditions. To do this, I first refine the date of the beginning of rising levels of Lake Titicaca, a precise and reliable proxy for more humid and stable conditions. Next, I compare demographic patterns based on a compilation of regional survey data and a summed probability distribution. A Bayesian model further refines the timing and span of the demographic surge. Finally, I present individual

Table 1 Summary of archaeological radiocarbon dates (see Supplement 1)

Site	Dates	Sources
Alto Pukara*	6	Beck (2004a, Table 3, 2004b, Table 1)
Camata	20	Steadman (1995, 10–31, Table 2); Eisentraut (1998, Table 3)
Ch'uxuqullu	4	Stanish *et al.* (2002, Figure 6); Stanish (2003, 303)
Chachichupa	17	Plourde (2006, Appendix C)
Chiripa	68	Ralph (1959, 56–57); Browman (1998, Table 1); Whitehead (2007, Appendix H)
Chuquiña	10	Fox (2007, Table 2·3)
Huatacoa	3	Cohen (2010, 122, 148, 157, Table B.4)
Jiskairumoko	26	Craig (2005, Table 7·6)
Kaillachuro	1	Craig (2005, Table 7·6)
Kella Kellani	3	McAndrews (1998, Table 1)
La Barca	1	Langlie *et al.* (2011, 75)
Markansa (PAM–05)	1	Jiménez (2012) cited in Capriles and Albarracín-Jordan (2013, 49)
Palermo	2	Stanish (2003, 118, 303)
Purimi (URR–001)	1	Méncias (2012) cited in Capriles and Albarracín-Jordan (2013, Table 1)
Pusno	3	Fox (2007, Table 2·3)
Qaluyu	7	Ralph (1959, 57); Chávez (1977, 1142–1147)
Quelcatani	9	Eisentraut (1998, Table 1)
San Andrés	3	Bermann and Castillo (1995, Table 1)
Sokotiña	1	Stuckenrath (1967, 335); Ponce (1970, Table 2)
Tiwanaku*	1	Kigoshi and Endo (1963, 116)
Wankarani	4	Wendt *et al.* (1962, 107); Ponce (1970, Table 2)
Wiskachuni	7	Herhahn (2004, 162–164, Table 4·3)
20 sites	191	

*Sites with outlier dates (see Supplement 1). These sites are not included in the analysis or the table totals, as both sites were first occupied well after the emergence of agropastoralism (for Tiwanaku, see Marsh 2012b).

models for 14 sites and combine them into a composite model that approximates the timing and span of the emergence of agropastoralism. At each of the sites, and at others without radiocarbon dates, there is evidence for a coincident, wide-spread and rapid integration of ceramic, agricultural, herding and hunting technologies and practices.

Methods: Bayesian Models

Bayesian models have been successfully deployed as statistically robust approach for developing fine-grained chronologies based on 'absolute' radiocarbon dates, given dates' inherent probabilistic uncertainty (Buck and Millard 2004; Bayliss 2009; Whittle *et al.* 2011). Bayesian models can incorporate stratigraphic sequences and cross-reference events, which can significantly improve temporal estimates. In an illustrative example, Bayliss and Bronk Ramsey (2004, 89–91) present a hypothetical 20-year phase dated by 20 simulated dates with 30-year errors. Looking at the overall span of error ranges, it would not be unexpected for an archaeologist to suggest that this phase lasted one to two centuries. Additional dates actually make the phase appear longer than it really is. In contrast, a Bayesian model correctly identifies the 20-year phase's beginning, end and duration; precision and accuracy improve with additional stratigraphic information or radiocarbon dates. Bayesian models are one of the few ways to effectively evaluate the possibility of rapid changes in radiocarbon-based chronologies, which is their purpose in this paper.

Models were run in OxCal 4·2 (Bronk Ramsey 2009). In the text I refer first to an age's median; the 68% probability range is in parentheses; the 95% range is in the tables. Dates are rounded by 10 years. This type of modelling can result in different results in multiple runs; differences in these models were no more than a decade or two. The specific parameters of each model are summarised in the text and available in Supplement 2. For other details of each date, such as the material dated, I refer the reader to the original publications cited in Table 1.

Dates are calibrated with the IntCal13 calibration curve (Reimer *et al.* 2013), a significant update from Stuiver and Reimer's (1993) calibration curve, which is the basis for the most widely cited and used climate and ceramic chronologies (Abbott *et al.* 1997a; Janusek 2003). While it would seem to make sense to use the Southern Hemisphere calibration curve, SHCal13 (Hogg *et al.* 2013), IntCal13 may in fact be more appropriate for a large part of South America (see Marsh 2012b, 205–206; Ogburn 2012, 223–224). SHCal13 is primarily based on data from other continents, so it may not reflect regional variability in South America. The Lake Titicaca Basin is located near the Intertropical Convergence Zone (ITCZ), where air from both hemispheres mix. The ITCZ shifts south during the austral summer, providing a different input of atmospheric carbon during the growing season (Abbott *et al.* 2000, Figure 1; Finucane *et al.* 2007, 581). Further complicating matters, the ITCZ has shifted southward during the Holocene (Mayle *et al.* 2000, 2294; Haug *et al.* 2001, 1307). For now, we cannot reliably estimate the ITCZ's influence on altiplano radiocarbon dates. One approach to dealing with this is to compare results from both curves (Ogburn 2012, 226–228). An alternative would be to mix the curves during calibration, resulting in less precise but more accurate age estimates, which is an appealing approach for comparisons to calendar dates (Bronk Ramsey, personal communication, 2013). For earlier periods, such as the one in question here, it seems sensible to continue using IntCal until dendrochronological data can define regional and temporal variability in atmospheric carbon (e.g. Morales *et al.* 2013).

Climate Shift at the End of the Middle Holocene

Climate reconstructions of the altiplano have consistently emphasised hyper-arid conditions during the Middle Holocene in sharp contrast to the warmer, wetter Late Holocene (Baker *et al.* 2001, 2005; Fritz *et al.* 2006; Theissen *et al.* 2008; Ledru *et al.* 2013). This interpretation is supported by a variety of proxies, the clearest being the level of Lake Titicaca, which closely tracks precipitation quantity, regularity, and overall effective moisture (Roche *et al.* 1992; Rowe and Dunbar 2004; Delclaux *et al.* 2007). During the Middle Holocene, lake levels were as low as 100 m below the modern level (e.g. Wirrmann and Oliveira Almeida 1987; Wirrmann and Mourguiart 1995; Seltzer *et al.* 1998; Cross *et al.* 2000; D'Agostino *et a*l. 2002). Towards the end of this period there was a rapid and significant rise, as much as 20 m within a few centuries, implying a massive change in lake volume (Abbott *et al.* 1997a, 177; Cross *et al.* 2000, 30). Given the correlated fluctuations in precipitation and effective moisture, this transition represents one of the most dramatic climate shifts in the entire Holocene.

The central issue here is the timing of this major lake level rise. It is clear that it took place in the centuries following 4000 BP, a consensus based on chemical and spectral analyses of pollen, diatoms, ostracods, seismic reflection pooling and sedimentology (e.g. Abbott *et al.* 1997a, 1997b; Mourguiart *et al.* 1998, 61; Seltzer *et al.* 1998, 169; Cross *et al.* 2000, 28; Paduano *et al.* 2003, 273; Tapia *et al.* 2003, 161; Baker *et al.* 2005). Most of these data are reliable at the millennium scale, and tend to locate the lake level rise in the middle of the millennium, roughly 3700–3300 cal BP. The rise was probably after 3700 cal BP. After this date, pollen records of Cyperaceae signal that the Lake's western littoral marshes were flooded. The rise was probably before 3300 cal BP. By this date, 'precipitation had increased sufficiently to support an expanded population of *Isoëtes* along the western lake boundary' (Paduano *et al.* 2003, 273).

Rising lake levels led to spillover into the previously desiccated Lake Wiñaymarka, the lake's sole outlet, and the Desaguadero River drainage into the central altiplano (Baucom and Rigsby 1999, 610). Outflow is very sensitive to lake level, which has significant impacts on the large, arid expanse south of Lake Titicaca. For example, in the second half of the twentieth century, lake levels varied by around 4 m, which translated into annual outflow averages that oscillated from less than 5 $m^3 s^{-1}$ to a maximum of 169 $m^3 s^{-1}$ (Roche *et al.* 1992, 77–79). The drainage south of Lake Titicaca was dry until sometime after 3680 cal BP, at which point lacustrine deposits began accumulating for the first time in millennia (Rigsby *et al.* 2005, 688). This date agrees well with the pollen data, which together define a maximum age for the beginning of regional climate change. Towards a more precise date of renewed and stable outflow into the central altiplano, I reassess the best available temporal data, radiocarbon dates from cores taken in Lake Wiñaymarka the southern part of Lake Titicaca (Abbott *et al.* 1997a).

Bayesian Reassessment of Lake Wiñaymarka Radiocarbon Dates

Four cores from Lake Wiñaymarka show a clear exposure surface (ES-1), which marks a period of erosion or lack of lacustrine deposition. At this time the lake was desiccated, and by extension, so was the Desaguadero River, except for minor and seasonal rain inputs. Prior to and below ES-1, there was very reduced sediment accumulation, around 0·24 cm/century. After and above ES-1, sediments have an elevated organic content consistent with shoreline remodelling. Accumulation was an order of magnitude faster, around 29·0 cm/century. Water levels rose very rapidly, perhaps 10 m in four centuries (Abbott *et al.* 1997a, 176).

Twenty-six dates stratigraphically bracket ES-1 without dating it directly, a task especially well suited to a Bayesian model (Supplement 2, Table 2). The model is composed of four sequences, one per core, in which the samples' chronological order is assumed to follow their relative depths (Abbott *et al.* 1997a, Tables 1 and 2). Cross-referencing ES-1 in multiple trials consistently resulted in a median date of 3545 cal BP, rounded by 1 year, and a 68% probability between 3600 and 3490 cal BP, rounded by 10 years. This is a precise estimate for an event that cannot be directly dated, with en error of just 52 years. It agrees well with less precise estimates from other studies (e.g. Cross *et al.* 2000; D'Agostino *et al.* 2002, 109).

The model incorporates an updated estimate of the lacustrine offset, which was applied to dates from gastropod shells and fish scales prior to calibration and modelling (Table 2). Abbott *et al.* (1997a, 172)

Table 2 Dates and depths from cores A–D in Lake Wiñaymarka (Abbott *et al*. 1997a, Tables 1 and 2), corrected with a lacustrine offset of 211 ± 62 years (see Table 3)

				Measured		Offset-corrected	
Core	Laboratory code (CAMS)	Depth below overflow level (cm)	Material	^{14}C age	error	^{14}C age	error
A	11974	1388	Gastropod shell	2730	70	2519	94
	11975	1408	Gastropod shell	3290	50	3079	80
	13600	1414	Fish scale	3050	100	2839	118
	11978	1414	Fish scale	3180	60	2969	86
	11976	1418	Gastropod shell	3570	60	3359	86
	ES-1	1419					
	13601	1422	Totora	3410	50	–	–
	11977	1423	Gastropod shell	3540	60	3329	86
B	13606	868	Gastropod shell	3040	70	2829	94
	13607	914	Gastropod shell	3410	70	3199	94
	ES-1	915					
	13608	919	Gastropod shell	3440	60	3229	86
	13609	919	Totora	3610	60	–	–
	13610	923	Totora	3720	60	–	–
C	17047	734	Gastropod shell	2750	100	2539	118
	17004	767	Gastropod shell	3220	60	3009	86
	17005	772	Gastropod shell	3360	60	3149	86
	ES-1	774					
	17006	802	Gastropod shell	3820	60	3609	86
	17048	802	Totora	3560	70	–	–
	17007	812	Gastropod shell	3500	100	3289	118
D	5761	421	Gastropod shell	2870	60	2659	86
	16996	428	Gastropod shell	2890	70	2679	94
	16997	439	Gastropod shell	3040	70	2829	94
	5763	451	Gastropod shell	3400	70	3189	94
	16998	479	Gastropod shell	3420	70	3209	94
	ES-1	480					
	4978	486	Totora	3210	80	–	–
	5741	491	Gastropod shell	6600	60	6389	86
	5742	501	Gastropod shell	6790	60	6579	86

*The three shaded pairs of dates are from identical depths and were treated as isochronous (using OxCal's Combine function). The pair of dates from core A was combined after applying the offset. The pairs from cores B and C were used to define the offset.

suggest an offset of 250 years, with no error, based on (1) paired radiocarbon and lead dates from an AD 1900 layer, though these data are not reported, and (2) five pairs of radiocarbon dates from lake cores, each with a gastropod shell (lacustrine) and totora reed sample (terrestrial), whose median differences range from 160 to 260 years (Table 3). The problem is that three of these pairs are inappropriate for defining an offset because they cannot be treated as isochronous. Depth differences of 2–7 cm may represent multiple centuries; in two pairs, dates are stratigraphically separated by ES-1. On the other hand, the two pairs from cores B and C are reliable. The offset based on these two pairs is 211 ± 62 years. Assuming all five pairs were reliable, the offset would not be much different: 203 ± 41 years. A Bayesian approach to these dates begins to address potential uncertainties with gastropod dates (Calaway 2005, 786). This estimate could be significantly improved with additional paired dates, a carbon-balance model (Yu *et al*. 2007) and more nuanced offset calculations (Jones and Nicholls 2001; Jones *et al*. 2007).

Environmental and Cultural Impacts of Rising Lake Levels

Increased precipitation and spillover of Lake Titicaca would have generated increasingly stable and humid conditions, reduced seasonal variability shorter dry seasons and longer rainy seasons (Abbott *et al*. 1997b, 78; Baucom and Rigsby 1999, 609; Rowe *et al*. 2002, 195; Rigsby *et al*. 2005, 688). These changes would have had a major impact on the ecosystem with which humans interacted, leading to increased quantities and reliability of riverine mammals, birds, amphibians, fish and plant life (McAndrews 2005, 43). A straightforward proxy for this is vegetation productivity. Fig. 1 shows a green halo of increased effective moisture surrounding the current extent of Lake Titicaca, which decreases with distance from Lake Titicaca and southward towards the central altiplano. Prior to rising lake levels, Lake Wiñaymarka and the Desaguadero River were desiccated, which would have resulted in very low vegetation productivity over a large area south of Lake Titicaca (a fascinating future research project would be to model vegetation productivity for the Middle Holocene and compare it to modern levels and

Table 3 Paired dates used to estimate the lacustrine offset for Lake Titicaca (from Abbott *et al*. 1997a, Table 1)

Laboratory Code (CAMS)	^{14}C age ± error		Material	Core	Depth (cm)	Depth relative to ES-1	Offset ± error*	
11976	3570	60	Gastropod shell	A	1418	above	160	78
13601	3410	50	Totora	A	1422	below		
13609	3610	60	Gastropod shell	B	919	below	170	85
13608	3440	60	Totora	B	919	below		
17006	3820	60	Gastropod shell	C	802	below	260	92
17048	3560	70	Totora	C	802	below		
16995	2480	60	Gastropod shell	D	373	above	240	92
4981	2240	70	Totora	D	375	above		
16998	3420	70	Gastropod shell	D	479	above	210	99
4978	3210	70	Totora	D	486	below		
Combined offset, based on cores B and C**							211	62

*Mean difference ± errors' sum of squares, following Stuiver *et al.* (1986, 982).
**Weighted mean ± errors' inverse sum of squares, following Ward and Wilson (1978).
There are five pairs of dates. Only the shaded two were used to calculate the overall offset at the bottom of the table.

distribution). Suddenly rising lake levels led to spillover southward into the central altiplano, providing stable, year-round moisture and vegetation productivity for the first time in millennia. Nearby microclimates would have emerged and been especially attractive for hunting, agriculture and camelid grazing (Bandy 2006, 215). The relative change would have been less pronounced west and north of Lake Titicaca, areas that were less impacted by the arid conditions of the Middle Holocene.

Human interactions with the environment can generate cultural change (e.g. Berglund 2003; Anderson *et al*. 2007). The region's inhabitants would have perceived a markedly more humid and productive environment with more resources. They would have been aware of increasingly predictable and stable climate and weather; this change was perhaps rapid enough to have been discerned within a single lifetime. An ecologically based model would expect humans and other mammals to have preferred the higher, moister valleys to the west and north of Lake Titicaca prior to rising lake levels. After this time, foragers would have modified their mobility circuits as increasing precipitation created new 'resource pulls' (Aldenderfer 1998, 139), in this case lacustrine and riverine landscapes in the southern Lake Titicaca Basin and central altiplano. Such a model predicts that a significant environmental change should coincide with cultural and demographic shifts, especially in the south, where the change was more dramatic.

Demographic Surge on the Altiplano

There was a major shift in mobility patterns, technology, economic strategies and demography from the Archaic (10,000–3500 BP) to Formative Period (3500–1500 BP). Hunting and gathering dominated during the Archaic; in the Formative, herding and farming became important at villages, which were focal points of growing populations and social complexity. However, the extent and timing of this sea change are not well known. I evaluate both by comparing three sets of data divided into three areas: west and north of Lake Titicaca, the southern Lake Titicaca Basin and the central altiplano (Fig. 1). I use two demographic proxies: (1) site counts from 15 full coverage surveys and (2) a summed probability distribution. This zeros in on the timing and speed of this shift, which is further refined by (3) a Bayesian model of dated contexts with and without ceramics, the same material distinction used in surface survey. Together, these data suggest that populations began increasing in the west and north before lake levels began to rise, after which these populations dropped and ones farther south surged, perhaps as a result of migration.

Population Histories Based on Surface Surveys

Population histories can be reconstructed with pedestrian survey data, which offer a picture of past occupations over large landscapes. The translation of survey data to demographic patterns is fraught with methodological uncertainties, but even so, large-scale changes should be clear, especially by comparing different data sets with a simple measure, such as number of sites per period. Site counts seem to be a reliable demographic proxy, as Archaic foragers and Formative agropasotralists generated settlement patterns with similar site-size distributions (Haas 2013). During field survey, occupations from the two periods can be distinguished by the absence or presence of ceramics, a general indicator of higher and lower degrees of mobility, respectively. The baseline expectation, or null hypothesis, is that regional population was relatively stable, and that there were similar numbers of sites per millennium during the 6500-year Archaic and the 2000-year Formative.

Substantial efforts by a number research teams in the last few decades have resulted in 15 full coverage pedestrian surveys that have covered an impressive 2005 km^2 and documented thousands of sites (Table 4). Overall, the Archaic is represented by 68

Table 4 Summary of Archaic and Formative data from major full-coverage surveys (see Fig. 1)

				Archaic		Formative	All periods	
Survey location	Area	Area (km^2)	Transect spacing (m)	Sites	Isolated finds	Sites	Sites	Sources
Ilave River Valley	Western highlands	41	10	142	–	44	464	Aldenderfer (1996); Tripcevich (2002)
Huenque River Valley	Western highlands	33	10–15	151	–	122*	300	Klink (2005)
Pukara Valley	Northwestern basin	49	25	–	–	43	143	Cohen (2010)
Huancané–Putina Valley	Northern basin	450	10–50	99	–	99	493	Cipolla (2005); Plourde (2006); Stanish *et al.* (2014)
Juli–Pomata	Southwestern basin	360	10–25	5	–	35	486	Stanish *et al.* (1997)
Island of the Sun	Southern island	20		3	–	59	180	Stanish and Bauer (2004)
Santiago de Huata Peninsula	Southeastern basin	63	20–50	1	2	50	94	Lémuz Aguirre (2001)
Taraco Peninsula	Southern basin	85	30	–	–	31	476	Bandy (2001)
Katari Valley	Southern basin	102	20–50	–	–	25	215	Janusek and Kolata (2004)
Lower Tiwanaku Valley	Southern basin	200	20–40	–	2	33	512	Albarracín-Jordan (1992)
Middle Tiwanaku Valley	Southern basin	173	30–60	–	–	16	587	Mathews (1992)
Upper Tiwanaku Valley	Southern basin	120	15–20	8	1	15	248	Calla Maldonado (2011)
Machaca	Southern basin	44	20–30	–	5	29	127	Gladwell (2007); Lémuz Aguirre (2011)
La Joya, Río Kochi, Belén	Central altiplano	427	30–50	–	–	17	135	McAndrews (2005)
Iroco	Central altiplano	38	5–15	35	–	45	185	Capriles *et al.* (2011)
Western and northern basin	4 surveys	573		392	–	308	1400	
Southern basin	9 surveys	967		17	10	293	2925	
Central altiplano	2 surveys	465		35	–	62	320	
Total	15 surveys	2005		444	10	663	4645	

*Total number of occupations.

sites per millennium, compared to the Formative's 332 a nearly five-fold increase, suggesting a marked demographic growth. This pattern varies by area: in the higher, more humid areas west and north of Lake Titicaca, there was a significant Archaic population. In the drier southern Lake Titicaca Basin and central altiplano, Archaic populations were very sparse, but became home to large villages in the Formative.

West and north of Lake Titicaca, four surveys covering some 570 km^2 report 60 Archaic and 154 Formative sites per millennium (Table 4). The two high-altitude surveys show very dense Archaic occupations and a drop in the Formative, which may reflect a modest demographic decrease. As with vegetation productivity, the diachronic difference in site counts is much more pronounced in the southern Lake Titicaca Basin. Nine surveys covering nearly 967 km^2 report 3 Archaic and 147 Formative sites per millennium. A similar pattern characterises the central altiplano, where two surveys covering 465 km^2 report 5 Archaic and 31 Formative sites per millennium. Without venturing to estimate population from site counts, these data clearly indicate demographic increase. Given the large areas of the surveys, this trend is strong enough to argue for a regional population boom, though is not fine-grained enough to reliably detect localised variation. This seems to be a reliable pattern, even if we take into account recovery bias.

There are a number of factors that bias surface data against Archaic sites more than Formative sites (Aldenderfer and Blanco, 2011, 536–538). Most are small lithic scatters that have been more vulnerable to taphonomic forces over longer periods of time. Rising lake levels have probably left many Archaic sites underwater. Surveys with research designs focused on identifying ceramic scatters usually employ transects spaced by around 30 m, while surveys targeting Archaic sites use 5–15 m transects and unsurprisingly report more Archaic sites (Table 4). Some sites have both ceramics and lithics, potential palimpsests of Archaic and Formative occupations that are difficult to distinguish. Temporal distinctions are muddied further by projectile point styles

Table 5 Dates of modelled boundaries for the transition to ceramics (cal BP)

Model	Modelled boundary	Median	68%	95%	±
Two overlapping phases	Start ceramic	3440	3470–3400	3510–3380	33
	End non-ceramic	3280	3380–3210	3430–3080	91
	Span	160	60–240	0–380	97
Trapezium boundary	Begin transition	3440	3470–3390	3530–3360	41
	End transition	3340	3390–3290	3420–3230	46
	Span	100	0–140	0–260	77

used during both periods (Klink and Aldenderfer 2005; Capriles *et al.* 2011, 464–465).

In the southern Lake Titicaca Basin, the entire Taraco Peninsula is covered by a 'low-density lithic scatter' (Bandy 2001, 88). Even when Archaic occupations are identified, it is difficult to determine which part of the 6500-year period is represented, a severe limitation in reconstructing population histories. Climatic data do discern differences between the Early, Middle and Late Archaic. Since climate was more amenable in the Early Archaic, a higher proportion of undifferentiated Archaic sites may be from this early time. In the drier periods that followed, higher proportions of Middle and Late Archaic sites may have been focused at ecological oases (Ledru *et al.* 2013).

Two surveys from the southern Lake Titicaca Basin are useful case studies to explore the potential impact of taphonomic biases. The survey of the Upper Tiwanaku Valley was much less affected than other surveys (Calla Maldonado 2011). It did not include the lakeshore, where Archaic sites are probably underwater. It used narrower 15–20 m transects, updated ceramic and projectile point chronologies, and targeted Archaic settlements. The data show remarkable changes in the settlement patterns. In the Late Archaic (6000–4000 BP), there were six sites covering a total of 0·14 ha and the largest site was 0·06 ha; in the Formative (3500–1900 BP), there were 15 sites covering 6·8 ha and the largest was a 5 ha village (Calla Maldonado 2011, Tables 5·4, 6·1). If there is any relationship at all between surface scatters and population, a remarkable demographic increase is evident. Showing a similar trend, the nearby Taraco Peninsula survey found no evidence of Archaic occupation at all. In two phases of the Early Formative (3500–2800 BP), there were 9 and 23 sites, respectively, most of which were over 3 ha. This suggests the peninsula was first occupied in the Formative by migrants who established villages with experienced remarkably high annual growth rates (Bandy 2001, 104–108). Both surveys suggest that despite biases against Archaic sites, Formative populations were much larger.

Even though Archaic occupations are likely underrepresented, any full-coverage survey, even with 30 m transects, should have the occasional luck of finding some minimal Archaic evidence (Bandy 2001, 280). Clearly there is variability over such a large region, such as in the notably denser Archaic occupations in Iroco's productive microenvironments (Capriles Flores 2011, 60–80; Ledru *et al.* 2013), but the overall trend of demographic increase is clear. Survey data cover large areas, making them useful for evaluating large scale spatial trends, but have reduced chronological resolution. The two periods in question cover thousands of years, so survey data cannot clarify exactly when or how fast changes took place. This important question can be addressed with a summed probability distribution.

Summed Probability Distribution

Summed probability distributions of radiocarbon dates are a useful demographic proxy, especially at larger temporal and spatial scales (see Williams 2012 and citations therein). The distribution of altiplano dates confirms the pattern suggested by survey data and clarifies the timing and speed of the change (Fig. 2). The distribution suggests a very low population during the dry Middle Holocene and a rise in population after 4000 cal BP until around 3600 cal BP. This increase is almost exclusively focused in the highlands west of Lake Titicaca, which notably drops after the beginning of the climate change. At this time, highland foragers may have moved to lower elevations. Farther south, population remains very low until around 3500 cal BP, when a number of dates from throughout the region appear. The steepest part of the curve is between about 3500 and 3300 cal BP, probably the period of most rapid population increase, which peaked around 3300–3250 cal BP. Importantly, this growth takes place after the onset of rising lake levels and is closely correlated with the transition to ceramics, described below (Fig. 2).

Summed probability distributions have recently become popular demographic proxies, but they do have a series of methodological issues related to intra- and inter-site sampling, sample size, calibration curve effects and taphonomic biases (Williams 2012, 579). The data set presented here is not ideal and suffers from many of these issues. However, it is useful for reading pronounced trends over longer intervals (Bamforth and Grund 2012, 1773). The curve identifies the timing of the pattern in the survey data. This chronology can be improved with a Bayesian model of the transition to ceramics, the most

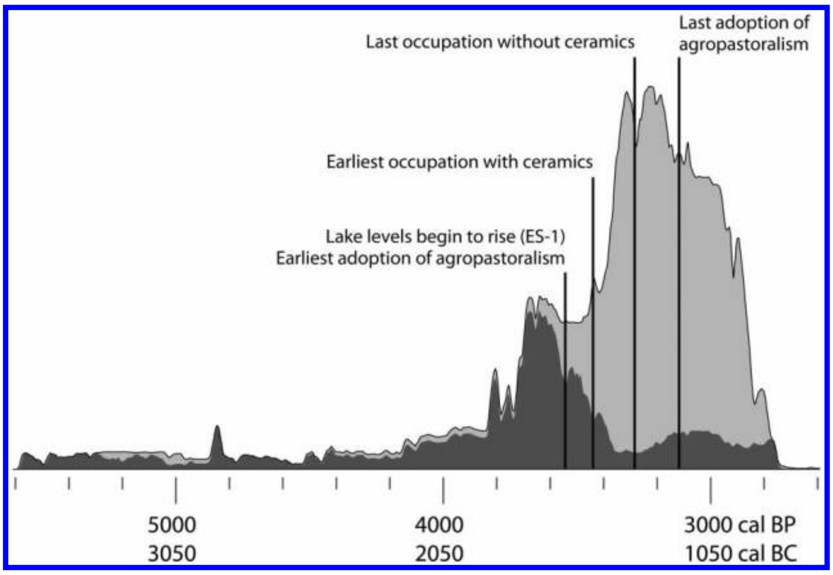

Figure 2 Summed probability distribution for radiocarbon dates between 4800 and 2800 radiocarbon years BP. The taller light grey curve sums dates from all 20 sites ($n = 108$, $\Delta T = 68$). The shorter dark grey curve sums dates from 4 sites west of Lake Titicaca (Camata, Kaillachuro, Jiskairumoko, and Quelcantani; $n = 39$, $\Delta T = 68$), showing that population was concentrated in this area before lake levels began to rise, after which it dropped. Vertical lines represent median dates for other modeled events.

common material distinction between Archaic and Formative sites during field survey.

Duration and Timing of the Transition to Ceramics

The Archaic–Formative transition is correlated with the presence or absence of ceramics in both survey and excavation contexts. As proposed by Stanish (2003, 99), I begin with the null hypothesis that the transition was gradual. This would not be unexpected, given the distance of over 500 km between the most distant sites, Qaluyu to Sokotiña (Fig. 1). The transition is modelled by exploring the temporal convergence of two phases, the first without associated ceramics (32 dates from 6 sites), and the second with associated ceramics (148 dates from 14 sites). The more conservative approach is to assume the phases overlapped, in other words, that there was a transition during which some groups used ceramics and others did not. This kind of transition can be modelled with OxCal's model for two overlapping phases.

The result shows that occupations with ceramics began around 3440 cal BP (3470–3400), and non-ceramic occupations continued until around 3280 cal BP (3380–3210). The remarkably brief difference of 160 years (60–240) suggests that groups with and without ceramics had a very short co-existence (Fig. 3, Table 5). Based on current data, it makes sense to use these estimates as maximum and minimum dates for undated contexts with and without ceramics, respectively, in both survey and excavation.

An alternate model assumes that ceramic-using groups gradually replaced non-ceramic-using groups, the basic concept behind a trapezium boundary (see Lee and Bronk Ramsey 2012). The same model with a trapezium boundary model suggests an even shorter period of transition, a mere 100 years (0–140). The similar results from both models suggest they offer robust temporal estimates (Table 5; Bayliss, personal communication, 2013). In both cases, the transition to ceramics took place *after* the beginning of the rise in lake levels (with a probability greater than 95%), according to comparisons with the modelled date for Lake Wiñaymarka's erosional event ES-1.

These data do not support the scenario of gradual adoption of ceramics. Instead, they support the hypothesis that this transition took place very rapidly, perhaps within a few generations, and no longer than a few centuries. During this short span, ceramic technology was used for the first time throughout a very large region. This technological shift was correlated with an equally radical and enduring change in demographics.

Source of the Altiplano Demographic Surge

Current data cannot distinguish between two possible scenarios for the altiplano's demographic surge: *in situ* growth or migration. In the first, mobile Archaic groups lived in the dry altiplano, focusing occupation at humid oases, leaving large parts of the altiplano with almost no Archaic material record. These patterns changed with improving climatic conditions. Leaving the oases to found villages, mobility decreased as population controls were relaxed, resulting in demographic growth (see Kelly 1995:232–259). In the second scenario, migrants moved into the increasingly

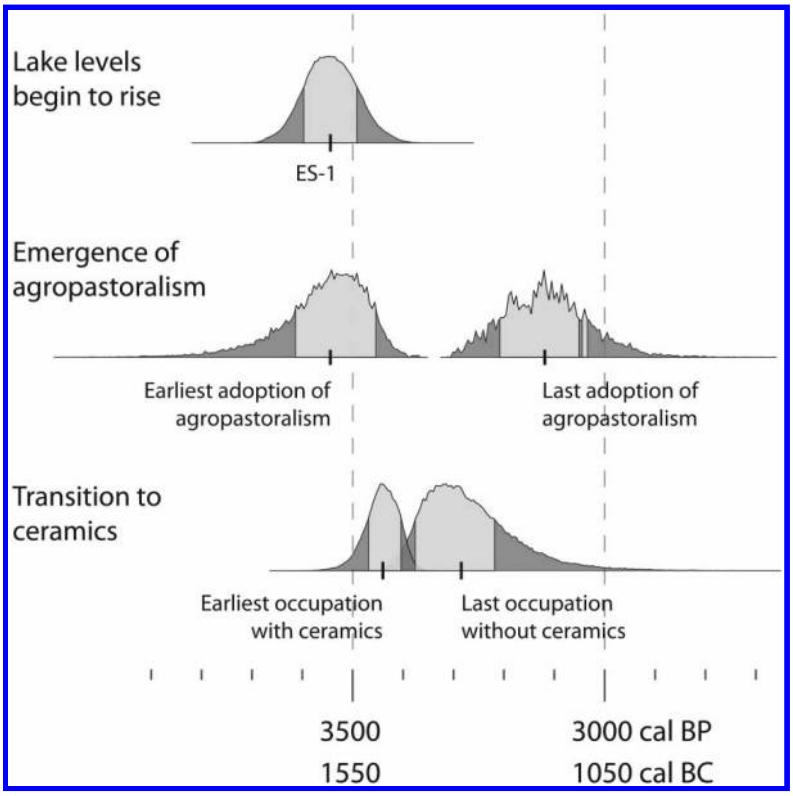

Figure 3 Comparison of modelled dates for the onset of rising lake levels, the emergence of agropastoralism and the transition to ceramics. Probabilities for each curve are indicated by lighter shading (68%) and darker shading (95%); the short vertical line at each curve's base indicates the median.

fertile and stable altiplano. They came from dense Archaic populations in the western highlands and expanded rapidly into an area that was essentially depopulated. Population movements can be very rapid in open landscapes; agricultural systems in particular are given to rapid dispersal (Rindos 1984). These immigrants carried a suite of technologies, namely the region's first ceramics, and founded a series of new villages separated by 500 km.

The migration scenario seems more amenable to current data and is supported by the summed probability distribution (Fig. 2), which suggests that population was focused in the western highlands before dropping as lake levels rose and ceramics were adopted. Migration also seems more likely based on individual sites: 14 of 16 were newly founded at this time, mostly south of Lake Titicaca (Table 5). The earliest newly founded site, Qaluyu, is located northwest of Lake Titicaca (Fig. 1, Table 5). After migration, population growth rose sharply, peaking around 3300–3150 cal BP. The summed probability distribution suggests another intriguing possibility to be tested with future research (Fig. 2). After millennia with low regional populations, there is a significant increase focused west of Lake Titicaca around 3750–3550 cal BP, a conspicuous prelude to the lake level rise and emergence of agropastoralism. This rapid population rise may represent low-level food producers (Smith 2001) who were rapidly intensifying their reliance on domestic plants and reducing mobility, also suggested by the associated ground stone and pit houses (Eisentraut 1998; Craig 2005).

A case can be made for both scenarios and they are not mutually exclusive. Either or both could have driven the radical change in mobility and settlement patterns, which seem to have taken place over the short span of around 3440 to 3280 cal BP. This closely correlates with altiplano's demographic increase, as suggested by the summed probability distribution peak from around 3500 to 3300 cal BP. These changes were preceded by the onset of rising lake levels, a sequence of events suggesting that there was a cultural response to changing environmental conditions. This cultural response included the adoption of an integrated set of practices that marked the emergence of agropastoralism.

The Emergence of Agropastoralism

The demographic shift was associated with a remarkable change in lifeways, as hunter–gatherers became agropastoralists. To define the timing and duration of this emergent episode, I developed 14 Bayesian models for each site with sufficient data, which I then cross-referenced in a composite model, following Bayliss *et al.* (2011). The individual-site models focus on temporal boundaries that represent when sites were founded or stratigraphic transitions to ceramics; they are also associated with other agropastoral

Table 6 Dates of modelled boundaries for individual sites and the composite model rounded by 10 years (cal BP)*

				Single site model			Composite model			
Site	Model	Boundary	Event	Median	95%	±	Median	95%	±	After ES-1?
Camata	Two-phase sequence	Simple	Earliest ceramics	**3140**	3310–2990	80	**3160**	3320–3030	72	1·00
Ch'uxuqullu	Simple sequence	Simple	Earliest ceramics	**3680**	4280–3250	290	**3410**	3620–3230	97	0·88
Chachichupa	One phase	Start	Founding	**3400**	3650–3270	102	**3390**	3540–3280	63	0·95
Chiripa	One phase	Start	Founding	**3490**	3650–3370	71	**3460**	3590–3370	53	0·85
Chuquiña	One phase	Start	Founding	**3360**	3690–3150	142	**3330**	3540–3150	97	0·96
Huatacoa	Sequence within phase	Start	Founding	**3350**	3700–3220	137	**3350**	3500–3240	64	0·98
Jiskairumoko	One phase	End	Earliest ceramics	**3360**	3490–3150	89	**3360**	3480–3190	72	0·99
Kella Kellani	One phase	Start	Founding	**3290**	4010–3020	306	**3290**	3520–3110	103	0·97
Palermo	Simple sequence	Start	Founding	**3540**	5250–2810	720	**3330**	3580–3040	140	0·94
Pusno	One phase	Start	Founding	**3350**	4270–3060	395	**3330**	3550–3140	101	0·96
Qaluyu	One phase	Start	Founding	**3630**	4450–3360	343	**3470**	3640–3360	68	0·79
San Andrés	One phase	Start	Founding	**3360**	5620–2890	643	**3300**	3550–3060	126	0·96
Wankarani	Simple sequence	Start	Founding	**3630**	5530–3000	675	**3390**	3620–3140	118	0·90
Wiskachuni	Sequence within phase	Start	Founding	**3180**	3490–2990	138	**3230**	3470–3060	101	0·99
La Barca	No model	(Single date)	Earliest occupation	**3220**	3350–3070	63				1·00
Sokotiña	No model	(Single date)	Earliest occupation	**3300**	3450–3160	74				0·99
Emergence of Agropastoral	Single phase		Start				**3540**	3750–3410	87	0·48
			End				**3120**	3280–2940	85	1·00
			Span				**370**	150–600	112	
Erosional Event ES-1 (Lake Wiñaymarka)							**3550**	3600–3490	52	
Temporal difference between Start of Agropastoral Emergence and ES-1							**0**	-230–180	101	

*Errors rounded by 1 year. The final column shows the probability that each event occurred after ES-1.

practices (Table 6, Supplement 2). I opted for simpler models where possible, and in most cases, all dates from a site were grouped as a single phase. There was often no effective difference between this and more elaborate models, especially at sites with many dates. All the boundaries have similar material associations, which is the rationale behind grouping them as a single phase in the composite model. This composite model cross-references individual-site model boundaries, with the goal of defining the chronology of the agropastoralism's emergence and to test its temporal correlation with rising lake levels.

The composite model's starting boundary is 3540 cal BP (3620–3450), an estimate of the beginning of the earliest agropastoral practices, and perhaps when the first site was founded by groups with these practices. The starting boundary was simultaneous with the onset of increasing lake levels, given the limits of chronological resolution of the data. Their distributions are strongly correlated (Fig. 3). It is likely, with a probability of 68%, that the two events took place within 100 years. These parallel developments marked the onset of an ecoculturally dynamic time. The temporal correlation suggests that pioneering foragers were adjusting their practices in close tandem with climate changes. These represent starting boundaries, after which lake levels continued to rapidly rise and large areas were settled by agropastoralists. All dated sites were founded or have a stratigraphic transition to ceramics that statistically fall after ES-1 (Table 6). The phase lasted some 370 years (250–480), ending around 3120 cal BP (3280–2940). By this date, agropastoral practices had already spread throughout the Lake Titicaca Basin and the central altiplano. Given current data, the starting and ending boundaries of this model may be useful as improved estimates for the beginning of the Formative and end of the Archaic Periods, respectively.

After hunting and gathering for thousands of years, large groups of people radically modified their lifestyles within a few centuries. This speaks to the flexibility of foragers, who immediately responded to improving climatic conditions by integrating new and existing technologies into a novel, remarkably stable economic lifestyle that continues to endure after some 3500 years. The longevity and origins of agropastoral practices are due to their capacity to increase reliability, not maximum output, in an unpredictable environment (Bandy 2005).

Agropastoral Practices and the Demographic Boom

The demographic boom was associated with a constellation of agropastoral practices, such as living in villages, making ceramics, farming, storing food, herding and hunting with bows. Pioneering examples of these practices can be identified a few centuries prior in the highlands west of Lake Titicaca, at sites such as Jiskairumoko (Craig 2005, 2011), which may explain how foragers were able to so quickly transform their lifestyles when the climate permitted it. These groups may be analogous to other examples of low-level food producers (Smith 2001), foragers who participated in co-evolutionary, mutualistic interactions with quinoa and camelids (Kuznar 1993). This may have unintentionally led to the earliest domestic plants and animals, the building blocks for widespread, rapid dispersal of pastoral and agricultural practices in a new environment (see Rindos 1984, 271–84).

There are few, overlapping dates for the earliest quinoa and ceramics. The impression is of a southward progression beginning in the western highlands, then the Titicaca Basin, and finally the central altiplano. The earliest ceramic date in the Andes may be from Quelcatani, 90 km southwest of Lake Titicaca, but the site's chronology is unclear (Eisentraut 1998, 64, 175; Stanish 2003, 102). (Dates from this site are not included in the models. Direct dates on *Chenopodium* seeds are much younger than charcoal dates at similar depths, suggesting some kind of unresolved stratigraphic disturbance (Eisentraut 1998, 175).) Ceramics appeared *after* domestic quinoa and ground stone, indicating that mobile foragers domesticated this plant (Eisentraut 1998, 61). There is a similar pattern at Camata on the western shores of Lake Titicaca, where domestic seeds were used by the site's foraging founders (Eisentraut 1998, 207–209), from a level dated to 3670 cal BP (3720–3580). (This section refers to calibrated, unmodelled dates.)

Domesticated quinoa was present in the southern Lake Titicaca Basin by 3430 cal BP (3550–3360; Bruno and Whitehead 2003, 350), a direct date on seeds from the earliest levels at Chiripa, which were associated with ceramics and other domesticates (Whitehead 2007, 236). A similar date, 3500 cal BP (3560–3390), comes from Qaluyu's deepest level in the northwestern basin, which included ceramics. Like other early ceramics throughout the region, these are thick, fibre-temper vessels, and part of assemblages with no decorated vessels (Browman 1980, 110–115; Stanish 2003, 102–104).

In the central altiplano, the earliest domesticated quinoa is a previously unknown variety, directly dated to 3220 cal BP (3330–3160); it was found in a domestic structure with evidence of ceramic production (Langlie *et al.* 2011, 75–76). Other central altiplano sites have ceramics in their earliest occupations whose calibrated medians fall between 3370 and 3200 cal BP. These sparse data suggest a southward expansion of ceramics and quinoa and support the scenario of migrants moving from the western highlands into the altiplano.

Domestic camelids were probably present prior to the emergence of agropastoralism, though a reliable chronology remains elusive. In the central highlands of Peru, Wheeler maintains that alpacas were present by roughly 6000 BP (Wheeler *et al.* 1976). Elsewhere in the Andes, proposed dates fall between 4500 and 3500 BP (e.g. Rick 1980; Browman 1989; Kuznar 1990; Bonavia 1999; Mengoni Goñalons and Yacobaccio 2006). It is difficult to identify a more precise date, as domestic and wild camelid bones are very similar. Morphometric comparisons have been able to make this distinction (Kent 1982) and expanding the range of comparative specimens has promise to improve this technique (Gasco 2013). The consensus is that animals were domesticated prior to 3500 BP and the founders of many altiplano sites seem to have already been herding llamas when they arrived. In the southern Lake Titicaca Basin, Chiripa's earliest levels include a nearly exclusive presence of camelid bones, some of which are morphometrically similar to modern llama bones (Kent 1982; Browman 1989; Moore *et al.* 1999). In the northern Lake Titicaca Basin, a similar picture characterises Huatacoa (Warwick 2012, 193). In the central altiplano, early faunal assemblages are dominated by camelid bones, in addition to indirect evidence for domestic animals (Ponce Sanginés 1970; Fox 2007; Capriles Flores 2011).

Shifts in lithic technology suggest that people began to hunt an increasing diversity of animals and began using or invented the bow. The earliest lithic darts, probably used with bows, date to the end of the Archaic, but the large majority are from the Formative, after around 3700 BP (Craig 2005, 475, 558, 580; Klink and Aldenderfer 2005, 52, Table 3·19). Like other new technologies, bow hunting first appeared in the western highlands and then became 'heavily integrated' in the Formative (Klink and Aldenderfer 2005, 54). Bow darts co-existed with other lithic technologies, suggesting diverse practices and prey. This may have included group hunting, a viable alternative for people living in villages.

Large-scale agriculture becomes evident towards the end of the proposed period for the emergence of agropastoralism, as groups expanded production with raised fields and hoes (see Bruno 2008, 18–25).

Raised fields are effective for reducing risks and improving yields at high altitudes, but their antiquity is often unclear (Erickson 2000, 329–345; Bandy 2005). Surveys have documented close associations with Formative sites and some raised fields may be as old as 3300 BP (Erickson 2000, 335–336; Stanish 2003, 109, 134). Lithic hoes were becoming more frequent, which may have been hafted and used as shovels for building or maintaining raised fields or terraces (Lémuz Aguirre 2001, 179; Janusek and Kolata 2004, 414–416; Bruno 2008, 460). West of Lake Titicaca, hoes are 'rare prior to 3200 cal BP,' and then become increasingly common (Rigsby *et al.* 2003, 182). On the Taraco Peninsula, there was a remarkable increase of olivine basalt hoes, possibly imported from the west, beginning around 2800 cal BP (Bandy 2001, 141–148). At Camata, hoes first appeared at around the same time and steadily became more common (Steadman 1995, 32, 41). In the central altiplano, one residence included dense refuse from hoe manufacture (Bermann and Castillo 1995, 394–395). Hoes may have been used for clearing timber, presumably to clear pasture or arable land. This practice is suggested by decreases in arboreal pollen taxa and increases in open-ground weed taxa beginning around 3100 cal BP (Paduano *et al.* 2003, 274); a similar pattern is visible at Chiripa a few centuries earlier (Whitehead 2007, 270). The similarity in dates throughout the region suggests that many groups begun modifying the landscape in similar ways around the same time, coincident with growing village populations.

All of these practices were integrated into an enduring agropastoral lifeway. At most sites, evidence for different agropastoral practices co-occurs, which makes sense because they are most effective and sustainable in combination. Prior to 3540 cal BP, the region was occupied by hunter–gatherers, most densely in the moist western highlands; after 3120 cal BP the entire region was occupied by agropastoralists (Table 6). These dates are the modelled boundaries' medians. An alternative would be to rely on ceramics as a proxy, which suggests an even narrower range: the earliest adoption of ceramics around 3440 cal BP, and the last one around 3300 cal BP (Fig. 3). These data speak against gradual change and piecemeal incorporation of ceramics, agriculture, and herding; instead they support a narrative of punctuated change that encompassed an extensive region.

This narrative should be tested against future data and alternative perspectives, with data from within the region and neighbouring regions. To the south, in the Cochabamba valley, there is a parallel picture of sparse Archaic occupation followed by dense early ceramic groups. A single-phase model of 19 dates from three sites estimates the first use of ceramics was around 3320 cal BP (3400–3230) (Gabelmann 2008, 173, Tables 2·3, 2·5, 2·6), where cultural and environmental changes seem to have been correlated (Williams *et al.* 2011). North of the Titicaca Basin, the earliest dates for ceramics are just a few centuries later (Mohr Chávez 1977, 1142–1147). The emergence of agropastoral practices on the altiplano may have been very extensive, and surely had impacts on surrounding regions. Refined chronologies are necessary to explore the nature of possible interactions and relationships during this dynamic time.

Conclusion

Chronological data do not support the null hypothesis of gradual change. In terms of the adoption of ceramics, there is a rapid, regional transition of less than two centuries beginning around 3440 cal BP and ending around 3300–3340 cal BP, depending on the model. Treating the adoption of ceramics as a proxy for other economic changes, one could argue that the highest rate of change was concentrated during this brief span. This span correlates with the demographic surge, which was most intense from around 3500 to 3300 cal BP, according to a summed probability distribution. Survey data from around the region confirm that this shift happened over an extensive geographic area, based on Archaic and Formative Period site counts.

The demographic boom was associated with a wholesale shift in economic practices, and there is coincident evidence for the initial integration of potting, farming, herding and bow hunting. A composite Bayesian model of 14 individual site models suggests that this developed around 3540–3120 cal BP. The starting date is statistically identical to the onset of improving environmental conditions, as foragers' changing practices closely tracked environmental changes.

Agropastoral technologies were probably first developed by low-level food producers in the highlands west of Lake Titicaca. The novelty and emergent nature of agropastoralism meant integrating novel and existing technologies in a new environment, coupled with a rapidly entrenched and enduring dependence on them. This was a large-scale cultural response by people living throughout a large region within perhaps two centuries. It is a testament to foragers' capacity to adapt and innovate in the face of shifting climatic conditions. These innovations remain the backbone of economic adaptions on the altiplano today.

The outlines of this shift have long been part of the archaeological literature, but this paper has been able to provide much more precise temporal estimates by incorporating recently processed dates into Bayesian models. The models have defined this as a period of accelerated change and not one of gradual transition. Moreover, they show just a very strong degree of correlation between major environmental cultural and environmental change. These methods can begin to clarify when the altiplano's 'big history' accelerated or decelerated, and to what extent variable cultural rhythms were correlated with environmental ones.

I hope this paper motivates greater focus on this hazy transitional period, during excavation and development of Bayesian models. A refined chronology may enable comparisons to other emergent agricultural episodes, such as those covered in *Current Anthropology*, in a 2009 section on Rethinking the Origins of Agriculture (volume 50, issue 5) and an extended 2011 issue on The Origins of Agriculture: New Data, New Ideas (volume 52, supplement 4). These broad-ranging discussions cover most areas of the world where agricultural emerged, but South America is all but absent. The Andean case offers an interesting comparison to other global cases, and it seems that there are some strikingly similarities in the rates of change, demography, pastoralism, agriculture and the adoption of ceramics. This case study is also related to global cultural impacts of Middle Holocene aridity. The Andean altiplano is a fascinating case study of accelerated and synchronous technological, cultural and climate change, synergistic factors behind an emergent phenomenon generated by large-scale ecocultural interactions.

Acknowledgements

Thanks to the community of Lake Titicaca archaeologists for stimulating discussions and assistance finding references and data. Guidance on the Bolivian Archaic came from Sergio Calla Maldonado, José Capriles, Claudia Rivera Casanovas, and Nico Tripcevich. Ramiro Barberena, David Browman, Valeria Cortegoso, Randy Haas and two anonymous reviewers read earlier drafts and made suggestions that significantly improved the manuscript. Gustavo Lucero prepared Figure 1. Bayesian models were developed through enlightening discussions and patient guidance in OxCal's online forum; many thanks are due to Alex Bayliss, Christopher Bronk Ramsey, Dan Contreras, Ray Kidd, Andrew Millard and Dennis Ogburn. I am grateful to all of these people. Errors of fact or interpretation are my own.

References

Abbott, M., Binford, M., Brenner, M. and Kelts, K. 1997a. A 3500 ^{14}C yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* **47**, 169–80.

Abbott, M., Seltzer, G., Kelts, K. and Southon, J. 1997b. Holocene paleohydrology of the tropical Andes from lake records. *Quaternary research* **47**, 70–80.

Abbott, M., Wolfe, B., Aravena, R., Wolfe, A. and Seltzer, G. 2000. Holocene hydrological reconstructions from stable isotopes and paleolimnology, Cordillera Real, Bolivia. *Quaternary Science Reviews* **19**, 1801–20.

Albarracín-Jordan, J. 1992. *Prehispanic and Early Colonial Settlement Patterns in the Lower Tiwanaku Valley, Bolivia.* Unpublished PhD. dissertation, Southern Methodist University, Dallas.

Aldenderfer, M. 1996. *Informe: reconocimiento arqueológico de la cuenca del Río Ilave*. Research report. Lima: Instituto Nacional de Cultura.

Aldenderfer, M. 1998. *Montane Foragers: Asana and the South-Central Andean Archaic.* Iowa City: University of Iowa.

Aldenderfer, M. and Flores Blanco, L. 2011. Reflexiones para avanzar en los estudios del período arcaico en Los Andes centro-sur. *Chungara* **43**, 531–50.

Anderson, D. G., Maasch, K. and Sandweiss, D. (eds.) 2007. *Climate Change and Cultural Dynamics: A Global Perspective on Mid-Holocene Transitions.* San Diego: Academic Press.

Baden, W. (ed.) 2005. *Nonlinear Models for Archaeology and Anthropology: Continuing the Revolution*. Farnham, UK: Ashgate.

Baker, P., Rigsby, C., Seltzer, G., Fritz, S., Lowenstein, T., Bacher, N. and Veliz, C. 2001. Tropical climate changes at millennial and orbital timescales on the Bolivian altiplano. *Nature* **409**, 698–701.

Baker, P., Fritz, S., Garland, J. and Ekdahl, E. 2005. Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation. *Journal of Quaternary Science* **20**, 655–62.

Bamforth, D. B. and Grund, B. 2012. Radiocarbon calibration curves, summed probability distributions, and early Paleoindian population trends in North America. *Journal of Archaeological Science* **39**, 1768–74.

Bandy, M. 2001. *Population and History in the Ancient Titicaca Basin*. Unpublished PhD. dissertation, University of California, Berkeley.

Bandy, M. 2005. Energetic efficiency and political expediency in Titicaca Basin raised field agriculture. *Journal of Anthropological Archaeology* **24**, 271–96.

Bandy, M. 2006. Early Village society in the Formative period in the southern Lake Titicaca Basin, pp. 210–36 in Isbell, W. and Silverman, H. (eds.), *Andean Archaeology III: North and South.* New York: Springer.

Baucom, P. and Rigsby, C. 1999. Climate and lake-level history of the northern Altiplano, Bolivia, as recorded in Holocene sediments of the Rio Desaguadero. *Journal of Sedimentary Research* **69**, 597–611.

Bayliss, A. 2009. Rolling out revolution: using radiocarbon dating in archaeology. *Radiocarbon* **51**, 123–47.

Bayliss, A. and Bronk Ramsey, C. 2004. Pragmatic Bayesians: a decade of integrating radiocarbon dates into chronological models, pp. 25–41 in Buck, C. and Millard, A. (eds.), *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries.* London: Springer.

Bayliss, A., Healy, F., Whittle, A. and Cooney, G. 2011. Neolithic narratives: British and Irish enclosure in their timescapes, pp. 682–847 in Whittle, A., Healy, F., Bayliss, A. and Allen, M. (eds.), *Gathering Time: Dating the Early Neolithic Enclosures of Southern Britain and Ireland.* Oxford: Oxbow.

Beck, R. 2004a. *Platforms of Power: House, Community, and Social Change in the Formative Lake Titicaca Basin.* Unpublished PhD. dissertation, Northwestern University, Illinois.

Beck, R. 2004b. Architecture and polity in the formative Lake Titicaca Basin, Bolivia. *Latin American Antiquity* **15**, 323–44.

Bentley, R. and Maschner, H. (eds.) 2003. *Complex Systems and Archaeology: Empirical and Theoretical Applications.* Salt Lake City: University of Utah.

Berglund, B. 2003. Human impact and climate changes—synchronous events and a causal link? *Quaternary International* **105**, 7–12.

Bermann, M. and Estévez Castillo, J. 1995. Domestic artifact assemblages and ritual activities in the Bolivian Formative. *Journal of Field Archaeology* **22**, 389–98.

Bonavia, D. 1999. The domestication of Andean camelids, pp. 127–45 in Politis, G. and Alberti, B. (eds.), *Archaeology in Latin America*. London: Routledge.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**, 337–60.

Browman, D. 1980. Tiwanaku Expansion and Altiplano Economic Patterns. *Estudios Arqueológicos* **5**, 107–20.

Browman, D. 1981. New Light on Andean Tiwanaku. *American Scientist* **69**, 408–19.

Browman, D. 1989. Origins and development of Andean pastoralism: an overview of the past 6000 years, pp. 256–75, in Clutton-Brock, J. (ed.), *The Walking Larder: Patterns of Domestication Pastoralism and Predation*. London: Unwin Hyman.

Browman, D. 1998. Lithic provenience analysis and emerging material complexity at Formative period Chiripa, Bolivia. *Andean Past* **5**, 301–24.

Bruno, M. 2008. *Waranq Waranqa: Ethnobotanical Perspectives on Agricultural Intensification in the Lake Titicaca Basin (Taraco Peninsula, Bolivia)*. Unpublished PhD. dissertation, Washington University, St. Louis.

Bruno, M. and Whitehead, W. 2003. Chenopodium cultivation and Formative period agriculture at Chiripa, Bolivia. *Latin American Antiquity* **14**, 339–56.

Buck, C. and Millard, A. (eds.) 2004. *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries.* London: Springer.

Calaway, M. 2005. Ice cores, sediments and civilisation collapse: a cautionary tale from Lake Titicaca. *Antiquity* **79**, 778–90.

Calla Maldonado, S. 2011. *Prospección arqueológica en el Valle Alto de Tiwanaku, contribuciones al estudio de la evolución del asentamiento prehispánico en el Valle de Tiwanaku*. Unpublished Licenciatura thesis, Universidad Mayor de San Andrés, La Paz.

Capriles, J., Calla Maldonado, S. and Albarracín-Jordán, J. 2011. Tecnología lítica y estrategias de subsistencia durante los periodos Arcaico y Formativo en el altiplano central, Bolivia. *Chungara* **43**, 455–68.

Capriles, J. M. and Albarracín-Jordan, J. 2013. The earliest human occupations in Bolivia: a review of the archaeological evidence. *Quaternary International* **301**, 46–59.

Capriles, and Flores, J. 2011. *The Economic Organization of early Camelid Pastoralism in the Andean Highlands of Bolivia*. Unpublished PhD. dissertation, Washington University, St. Louis.

Cipolla, L. M. 2005. Preceramic period settlement patterns in the Huancané-Putina River Valley, northern Titicaca Basin, Peru, pp. 55–63 in Stanish, C., Cohen, A. and Aldenderfer, M. (eds.), *Advances in Titicaca Basin Archaeology–1*. Los Angeles: Costen Institute of Archaeology.

Cohen, A. 2010. *Ritual and Architecture in the Titicaca Basin: The Development of the Sunken Court Complex in the Formative Period.* Unpublished PhD. dissertation, University of California, Los Angeles.

Craig, N. 2005. *The Formation of early Settled Villages and the Emergence of Leadership: A Test of Three Theoretical Models in the Rio Ilave, Lake Titicaca Basin, Southern Peru*. Unpublished PhD. dissertation, University of California, Santa Barbara.

Craig, N. 2011. Cultural dynamics, climate, and Landscape in the south-central Andes during the mid–late Holocene: a consideration of two socio-natural perspectives. *Chungara* **43**, 367–91.

Cross, S., Baker, P., Seltzer, G., Fritz, S. and Dunbar, R. 2000. A new estimate of the Holocene lowstand level of Lake Titicaca, central Andes, and implications for tropical palaeohydrology. *The Holocene* **10**, 21–32.

D'Agostino, K., Seltzer, G., Baker, P., Fritz, S. and Dunbar, R. 2002. Late-Quaternary lowstands of Lake Titicaca: evidence from high-resolution seismic data. *Palaeogeography, Palaeoclimatology, Palaeoecology* **179**, 97–111.

Delclaux, F., Coudrain, A. and Condom, T. 2007. Evaporation estimation on Lake Titicaca: a synthesis review and modelling. *Hydrological Processes* **21**, 1664–77.

Eisentraut, P. 1998. *Macrobotanical Remains from Southern Peru: A Comparison of Late Archaic-Early Formative Period Sites from the Puna and Suni Zones of the Western Titicaca Basin*. Unpublished PhD. dissertation, University of California, Santa Barbara.

Erickson, C. 2000. The Lake Titicaca basin: a precolumbian built landscape, pp. 311–56 in Lentz, D. (ed.), *Imperfect Balance: Landscape Transformations in the Precolumbian Americas.* New York: Columbia University.

Finucane, B., Valdez, J., Pérez Calderon, I., Pomacanchari, C., Valdez, L. and O'Connell, T. 2007. The end of empire: new radiocarbon dates from the Ayacucho Valley, Peru, and their implications for the collapse of the Wari State. *Radiocarbon* **49**, 579–92.

Fox, J. 2007. *Time and Process in an early Village Settlement System on the Bolivian Southern Altiplano*. Unpublished PhD. dissertation, University of Pittsburgh.

Fritz, S. C., Baker, P. A., Tapia, P. and Garland, J. 2006. Spatial and temporal variation in cores from Lake Titicaca, Bolivia/Peru during the last 13,000 yrs. *Quaternary International* **158**, 23–29.

Gabelmann, O. 2008. *Keramikproduktion in Santa Lucía: Ein blick auf die 'peripherie' des Formativums im südzentralen andenraum*. Unpublished PhD. dissertation, Freie Universität Berlin.

Gasco, A. 2013. *Caza y pastoreo de camélidos en la frontera meridional del 'mundo' andino. Una aproximación osteométrica*. Unpublished PhD. dissertation, Universidad Nacional de Córdoba, Argentina.

Gladwell, R. 2007. El rango de Machaca (Quimsachata) como zona de producción pastoral: Implicaciones históricas para comprender paisajes del pasado, pp. 22–65 in Janusek, J. W. and Plaza Martinez, V. (eds.), *Khonkho e Iruhito: Tercer informe preliminar del proyecto Jach'a Machaca*. Report presented to the Unidad Nacional de Arqueología, La Paz, Bolivia.

Gosling, D. and Williams, J. 2013. Ecosystem service provision sets the pace for pre-Hispanic societal development in the central Andes. *The Holocene* **23**, 1619–24.

Haas, W. R. 2013. The forager-farmer transition in the Ilave Basin, Peru: site size, residential mobility, and neutral theory. Poster presented at the 53rd Annual Meeting of the Institute of Andean Studies, Berkeley, CA.

Hastorf, C. 2008. The Formative period in the Titicaca Basin, pp. 545–61 in Silverman, H. and Isbell, W. (eds.), *The Handbook of South American Archaeology.* New York: Springer.

Haug, G., Hughen, K., Sigman, D., Peterson, L. and Röhl, U. 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. *Science* **293**, 1304–8.

Herhahn, C. 2004. *Moving to Live: A Pastoral Mobility Model from the South-Central Andes, Peru*. Unpublished PhD. dissertation, University of California, Santa Barbara.

Hogg, A., Hua, Q., Blackwell, P., Niu, N., Buck, C., Guilderson, T., Heaton, T., Palmer, J., Reimer, P., Reimer, R., Turney, C. and Zimmerman, S. 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 cal yr BP. *Radiocarbon* **55**, 1889–903.

Janusek, J. 2003. Vessels, time, and society: toward a chronology of ceramic style in the Tiwanaku heartland, pp. 30–92 in Kolata, A. (ed.), *Tiwanaku and its Hinterland: Archaeological and Paleoecological Investigations of an Andean Civilization, Vol. 2: Urban and Rural Archaeology.* Washington, DC: Smithsonian Institution.

Janusek, J. and Kolata, A. 2004. Top-down or bottom-up: rural settlement and raised field agriculture in the Lake Titicaca Basin, Bolivia. *Journal of Anthropological Archaeology* **23**, 404–30.

Jiménez, V. 2012. *La movilidad de los cazadores–recolectores en el Valle de Markanasa durante el Período Arcaico (7700–3200 AP)*. Unpublished Licenciatura thesis, Universidad Mayor de San Andrés, La Paz.

Jones, M. and Nicholls, G. 2001. Reservoir offset models for radiocarbon calibration. *Radiocarbon* **43**, 119–24.

Jones, M., Petchey, F., Green, R., Sheppard, P. and Phelan, M. 2007. The marine ΔR For Nenumbo (Solomon Islands): a case study in calculating reservoir offsets from paired sample data. *Radiocarbon* **49**, 95–102.

Kelly, R. 1995. *The Foraging Spectrum: Diversity in Hunter–Gatherer Lifeways.* Washington, DC: Smithsonian Institution Press.

Kent, J. 1982. *The Domestication and Exploitation of the South American Camelids: Methods of Analysis and their Application to Circum-Lacustrine Sites in Bolivia and Peru.* Unpublished PhD. dissertation, Washington University, St. Louis.

Kigoshi, K. and Endo, K. 1963. Gakushuin Natural Radiocarbon Measurements II. *Radiocarbon* **5**, 109–17.

Klink, C. 2005. Archaic period research in the Rio Huenque valley, Peru, pp. 13–24 in Stanish, C., Cohen, A. and Aldenderfer, M. (eds.), *Advances in Titicaca Basin Archaeology–1*. Los Angeles: Cotsen Institute of Archaeology.

Klink, C. and Aldenderfer, M. 2005. A projectile point chronology for the south-central Andean highlands, pp. 25–54 in Stanish, C., Cohen, A. and Aldenderfer, M. (eds.), *Advances in Titicaca Basin archaeology–1.* Los Angeles: Cotsen Institute of Archaeology.

Kuznar, L. 1990. Pastoralismo temprano en la sierra alta del Departamento de Moquegua, Perú. *Chungara* **24/25**, 53–68.

Kuznar, L. 1993. Mutualism between Chenopodium, herd animals, and herders in the south central Andes. *Mountain Research and Development* **13**, 257–65.

Langlie, B., Hastorf, C., Bruno, M., Bermann, M., Bonzani, R. and Castellón Condarco, W. 2011. Diversity in Andean chenopodium domestication: describing a new morphological type from La Barca, Bolivia, 1300–1250 BC. *Journal of Ethnobiology* **31**, 72–88.

Ledru, M.-P., Jomelli, V., Bremond, L., Ortuño, T., Cruz, P., Bentaleb, I., Sylvestre, F., Kuentz, A., Beck, S. and Martin, C. 2013. Evidence of moist niches in the Bolivian Andes during the mid-Holocene arid period. *The Holocene* **23**, 1547–59.

Lee, S. and Bronk Ramsey, C. 2012. Development and application of the trapezoidal model for archaeological chronologies. *Radiocarbon* **54**, 107–22.

Lehner, M. 2000. Fractal house of Pharaoh: Ancient Egypt as a complex adaptive system, a trial formulation, pp. 275–353 in Kohler, T. and Gumerman, G. (eds.), *Dynamics in Human and Primate Societies: Agent-Based Modelling of Social and Spatial Processes*. Oxford: Oxford University Press.

Lémuz Aguirre, C. 2001. *Patrones de asentamiento arqueológico en la Península de Santiago de Huata, Bolivia*. Unpublished Licenciatura thesis, Universidad Mayor de San Andrés, La Paz.

Lémuz Aguirre, C. 2011. Patrones de asentamiento arqueológico en el área de influencia del sitio de Khonkho Wankane. *Nuevos Aportes* **5**, 31–70.

Marsh, E. 2012a. *The emergence of Tiwanaku: Domestic practices and regional traditions at Khonkho Wankane and Kk'araña*. Unpublished PhD. dissertation, University of California, Santa Barbara.

Marsh, E. 2012b. A Bayesian re-assessment of the earliest radiocarbon dates from Tiwanaku, Bolivia. *Radiocarbon* **54**, 203–18.

Mathews, J. 1992. *Prehispanic Settlement and Agriculture in the Middle Tiwanaku Valley, Bolivia*. Unpublished PhD. dissertation, University of Chicago.

Mayle, F., Burbridge, R. and Killeen, T. 2000. Millennial-scale dynamics of southern Amazonian rain forests. *Science* **290**, 2291–4.

McAndrews, T. 1998. *Early Village-Based Society and Long-Term Cultural Evolution in the South-Central Andean altiplano.* Unpublished PhD. dissertation, University of Pittsburgh.

McAndrews, T. 2005. *Wankarani Settlement Systems in Evolutionary Perspective: A Study in Early Village-Based Society and Long-Term Cultural Evolution in the South-Central Andean Altiplano.* Pittsburgh: University of Pittsburgh.

McGlade, J. 1995. Archaeology and the ecodynamics of human-modified landscapes. *Antiquity* **69**, 113–32.

Méncias, J. 2012. *Aplicación de la arqueología rupestre en el complejo arqueológico de Pumiri (Provincia Sajama del Departamento de Oruro, Bolivia)*. Unpublished Licenciatura thesis, Universidad Mayor de San Andrés, La Paz.

Mengoni Goñalons, G. and Yacobaccio, H. 2006. The domestication of south american camelids: a view from the south-central Andes, pp. 228–44 in Zeder, M., Bradley, D., Emshwiller, E. and Smith, B. (eds.), *Documenting Domestication: New genetic and Archaeological Paradigms.* Los Angeles: University of California.

Mohr Chávez, K. 1966. *An Analysis of the Pottery of Chiripa, Bolivia: A Problem in Archaeological Classification and Inference*. Unpublished Master's thesis, University of Pennsylvania, Philadelphia.

Mohr Chávez, K. 1977. *Marcavalle: The Ceramics from an Early Horizon site in the Valley of Cusco, Peru, and Implications for South Highland Socio-Economic Interaction*. Unpublished PhD. dissertation, University of Pennsylvania, Philadelphia.

Moore, K. M., Steadman, D. and de France, S. 1999. Herds, fish, and fowl in the domestic and ritual economy of formative Chiripa, pp. 105–16 in Hastorf, C. (ed.), *Early Settlement at Chiripa, Bolivia: Research of the Taraco Archaeological Project*. Berkeley: University of California.

Morales, M., Nielsen, A. and Villalba, R. 2013. First dendroarchaeological dates of prehistoric contexts in South America: Chullpas in the Central Andes. *Journal of Archaeological Science* **40**, 2393–401.

Mourguiart, P., Corrège, T., Wirrmann, D., Argollo, J., Montenegro, M. E., Pourchet, M. and Carbonel, P. 1998. Holocene palaeohydrology of Lake Titicaca estimated from an ostracod-based transfer function. *Palaeogeography, Palaeoclimatology, Palaeoecology* **143**, 51–72.

Ogburn, D. 2012. Reconceiving the chronology of Inca imperial expansion. *Radiocarbon* **54**, 219–37.

Paduano, G., Bush, M., Baker, P., Fritz, S. and Seltzer, G. 2003. A vegetation and fire history of Lake Titicaca since the last glacial maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**, 259–79.

Pauketat, T. 2001. Practice and history in archaeology: an emerging paradigm. *Anthropological Theory* **1**, 73–98.

Plourde, A. 2006. *Prestige Goods and their role in the Evolution of Social Ranking: A Costly Signaling Model with data from the Formative Period of the Northern Lake Titicaca Basin, Peru.* Unpublished PhD. dissertation, University of California, Los Angeles.

Ponce Sanginés, C. 1970. *Las culturas de Wankarani y Chiripa y su relación con Tiwanaku*. La Paz: Academia Nacional de Ciencias de Bolivia.

Ralph, E. 1959. University of Pennsylvania Radiocarbon Dates III. *American Journal of Science Radiocarbon Supplement* **1**, 45–58.

Reimer, P., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Bronk Ramsey, C., Grootes, P., Guilderson, T., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffman, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, A., Marian Scott, E., Southon, J., Staff, R., Turney, C. and van der Plicht, J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**, 1869–87.

Rick, J. 1980. *Prehistoric Hunters of the High Andes*. New York: Academic.

Rigsby, C., Baker, P. and Aldenderfer, M. 2003. Fluvial history of the Rio Ilave valley, Peru, and its relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**, 165–85.

Rigsby, C., Bradbury, J., Baker, P., Rollins, S. and Warren, M. 2005. Late Quaternary palaeolakes, rivers, and wetlands on the Bolivian Altiplano and their palaeoclimatic implications. *Journal of Quaternary Science* **20**, 671–91.

Rindos, D. 1984. *The Origins of Agriculture: An Evolutionary Perspective*. Orlando: Academic.

Roche, M., Bourges, J., Cortes, J. and Mattos, R. 1992. Climotology and Hydrology of the Lake Titicaca Basin, pp. 63–88 in Dejoux, C. and Iltis, A. (eds.), *Lake Titicaca: A Synthesis of Limnological Knowledge.* Dordrecht: Kluwer.

Rowe, H. and Dunbar, R. 2004. Hydrologic-energy balance constraints on the Holocene lake-level history of lake Titicaca, South America. *Climate Dynamics* **23**, 439–54.

Rowe, H., Dunbar, R., Mucciarone, D., Seltzer, G., Baker, P. and Fritz, S. 2002. Insolation, moisture balance and climate change on the South American altiplano since the Last Glacial Maximum. *Climatic Change* **52**, 175–99.

Rowley-Conwy, P. 2001. Time, change and the archaeology of hunter-gatherers: how original is the 'Original Affluent Society'?, ppp. 39–72 in Panter-Brick, C., Layton, R. and Rowley-Conwy, P. (eds.), *Hunter–Gatherers: An Interdisciplinary Perspective*. Cambridge: Cambridge University Press.

Sawyer, R. 2004. The mechanisms of emergence. *Philosophy of the Social Sciences* **34**, 260–82.

Seltzer, G., Baker, P., Cross, S., Dunbar, R. and Fritz, S. 1998. High-resolution seismic reflection profiles from Lake Titicaca, Peru–Bolivia: evidence for Holocene aridity in the tropical Andes. *Geology* **26**, 167–70.

Smith, B. 2001. Low-level food production. *Journal of Archaeological Research* **9**, 1–43.

Stanish, C. 2003. *Ancient Titicaca: The Evolution of Complex Societies in Southern Peru and Northern Bolivia.* Berkeley: University of California.

Stanish, C. and Bauer, B. (eds.) 2004. *Archaeological Research on the Islands of the Sun and Moon, Lake Titicaca, Bolivia: Final results from the Proyecto Tiksi Kjarka*. Los Angeles: Cotsen Institute of Archaeology.

Stanish, C., Chávez, J. C., Plourde, A. and LaFavre, K. 2014. *The Northern Titicaca Basin Archaeological Research Program—Volume I. The Huancané-Putina Survey.* Ann Arbor: University of Michigan.

Stanish, C., de la Vega, E., Steadman, L., Chávez Justo, C., Frye, K., Onofre Mamani, L., Seddon, M. and Calisaya Chuquimia, P. 1997. *Archaeological Survey in the Juli–Desaguadero Region of Lake Titicaca Basin, Southern Peru*. Chicago: Field Museum of Natural History.

Stanish, C., Burger, R., Cipolla, L., Glascock, M. and Quelima, E. 2002. Evidence for early long-distance obsidian exchange and watercraft use from the southern Lake Titicaca Basin of Bolivia and Peru. *Latin American Antiquity* **13**, 444–54.

Steadman, L. 1995. *Excavations at Camata: An early Ceramic Chronology for the Western Titicaca Basin, Peru*. Unpublished PhD. dissertation, University of California, Berkeley.

Stuckenrath, R. 1967. University of Pennsylvania Radiocarbon Dates X. *Radiocarbon* **9**, 333–45.

Stuiver, M., Pearson, G. and Braziunas, T. 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. *Radiocarbon* **28**, 980–1021.

Stuiver, M. and Reimer, P. 1993. Extended 14C database and revised CALIB radiocarbon calibration program. *Radiocarbon* **35**, 215–30.

Tapia, P., Fritz, S., Baker, P., Seltzer, G. and Dunbar, R. 2003. A Late Quaternary diatom record of tropical climatic history from Lake Titicaca (Peru and Bolivia). *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**, 139–64.

Theissen, K., Dunbar, R., Rowe, H. and Mucciarone, D. 2008. Multidecadal- to century-scale arid episodes on the northern Altiplano during the middle Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **257**, 361–76.

Tripcevich, N. 2002. *Viewshed Analysis of the Ilave River Valley*. Unpublished data paper, University of California, Santa Barbara.

van der Leeuw, S. and McGlade, J. (eds.). 1997. *Time, Process, and Structured Transformation in Archaeology*. New York: Routledge.

Ward, G. and Wilson, S. 1978. Procedures for comparing and combining radiocarbon age determinations: a critique. *Archaeometry* **20**, 19–31.

Warwick, M. 2012. *In the Shadow of the Peñon: A Zooarchaeological Study of Formative Diet, Economy, and Sociopolitics in the Rio Pukara Valley, Peru*. Unpublished PhD. dissertation, University of Wisconsin, Milwaukee.

Wendt, I., Schneekloth, H. and Budde, E. 1962. Hannover radiocarbon measurements I. *Radiocarbon* **4**, 100–8.

Wheeler, J., Pires-Ferreira, E. and Kaulicke, P. 1976. Preceramic animal utilization in the central Peruvian Andes. *Science* **194**, 483–90.

Whitehead, W. 2007. *Exploring the Wild and Domestic: Paleoethnobotany at Chiripa, a Formative Site in Bolivia*. Unpublished PhD dissertation, University of California, Berkeley.

Whittle, A., Healy, F., Bayliss, A. and Allen, M. (eds.) 2011. *Gathering Time: Dating the Early Neolithic Enclosures of Southern Britain and Ireland*. Oxford: Oxbow.

Williams, A. 2012. The use of summed radiocarbon probability distributions in archaeology: a review of methods. *Journal of Archaeological Science* **39**, 578–89.

Williams, J., Gosling, W., Coe, A., Brooks, S. and Gulliver, P. 2011. Four thousand years of environmental change and human activity in the Cochabamba Basin, Bolivia. *Quaternary Research* **76**, 58–68.

Wirrmann, D. and Mourguiart, P. 1995. Late Quaternary spatio-temporal limnological variations in the Altiplano of Bolivia and Peru. *Quaternary Research* **43**, 344–54.

Wirrmann, D. and Oliveira Almeida, L. F. 1987. Low Holocene level (7700 to 3650 years ago) of Lake Titicaca (Bolivia). *Palaeogeography, Palaeoclimatology, Palaeoecology* **59**, 315–23.

Yu, S., Shen, J. and Colman, S. 2007. Modeling the radiocarbon reservoir effect in lacustrine systems. *Radiocarbon* **49**, 1241–54.